Assessment and long-term monitoring of the hydrologic cycle with space-based isotope observations

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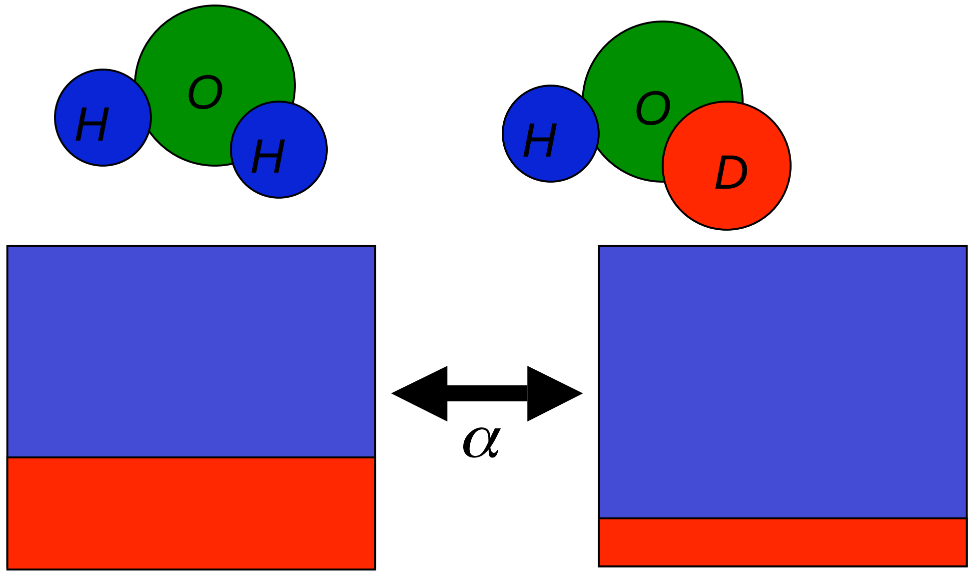
Overview

- Isotope measurement are inherently integrative
- Use water isotopes to measure hydrologic ***exchange/flux***
- ***Balance*** of numerous exchange processes establish mean state
- Isotopes give a measure "strength" of the hydrologic cycle
- Long term monitoring gives change in processes (i.e., acceleration)
- Unique view of balance of water sources and transport

Conclusions

- Process: Extra tropics condensation-evaporation cycling
- Process: Tropics also has water recycling by clouds
- Process: Tropical land has important transpiration source
- Process: Regions of convection not the same
  ("arid" versus moist regimes)
- TES HDO data can be used to estimate budget terms
  (right answer for the right reason)
- Follow-on mission needed to provide monitoring of flux

Reminder of isotope physics



liquid
(e.g., ocean)

vapor
(e.g., atmosphere)

Ratio of HDO to H_2O

Measured as a difference from ocean water.

$$\delta = \frac{R}{R_{ocn}} - 1$$

Two simple isotope models…

Condensation

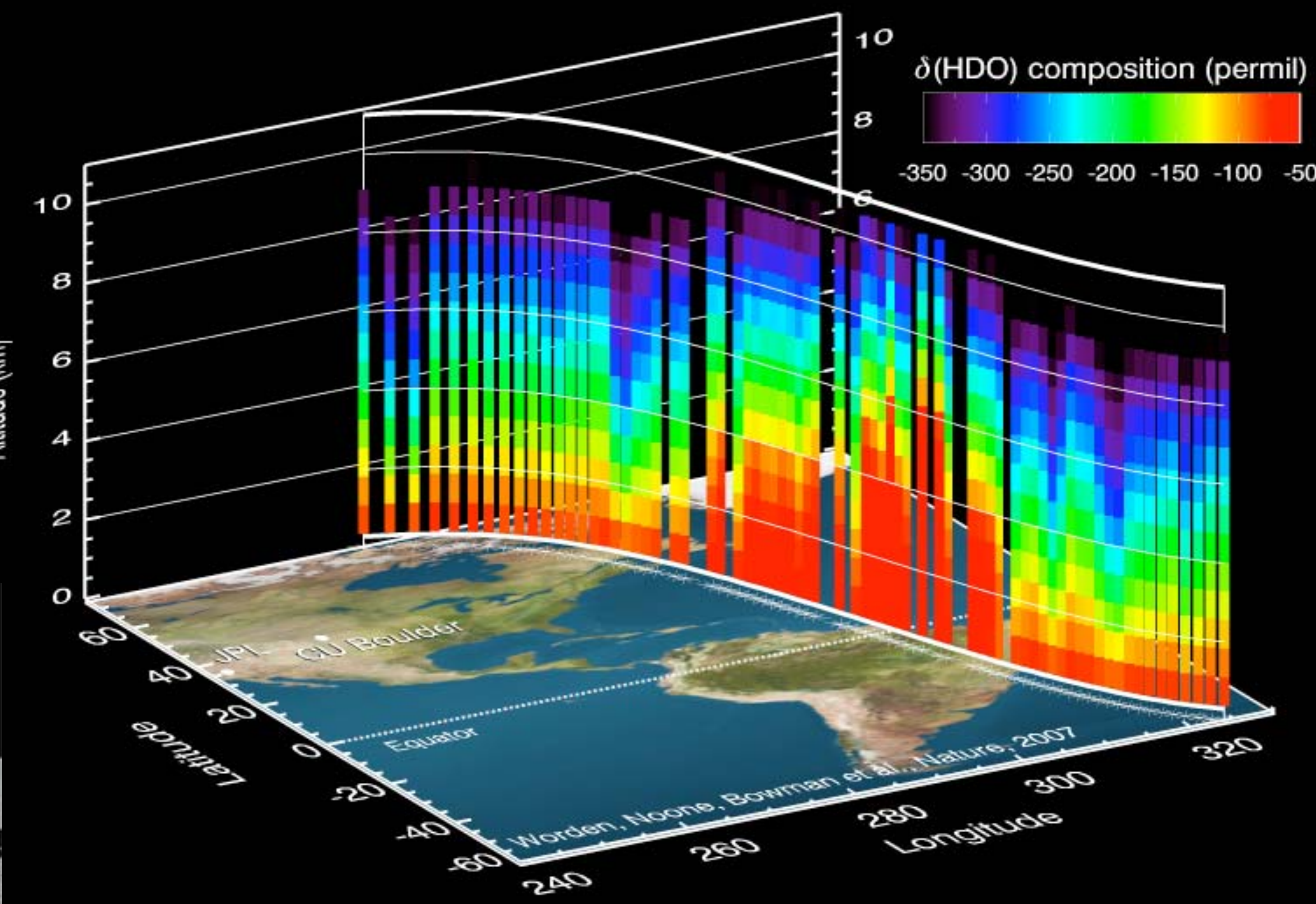
Vapour becomes depleted as heavy removed preferentially

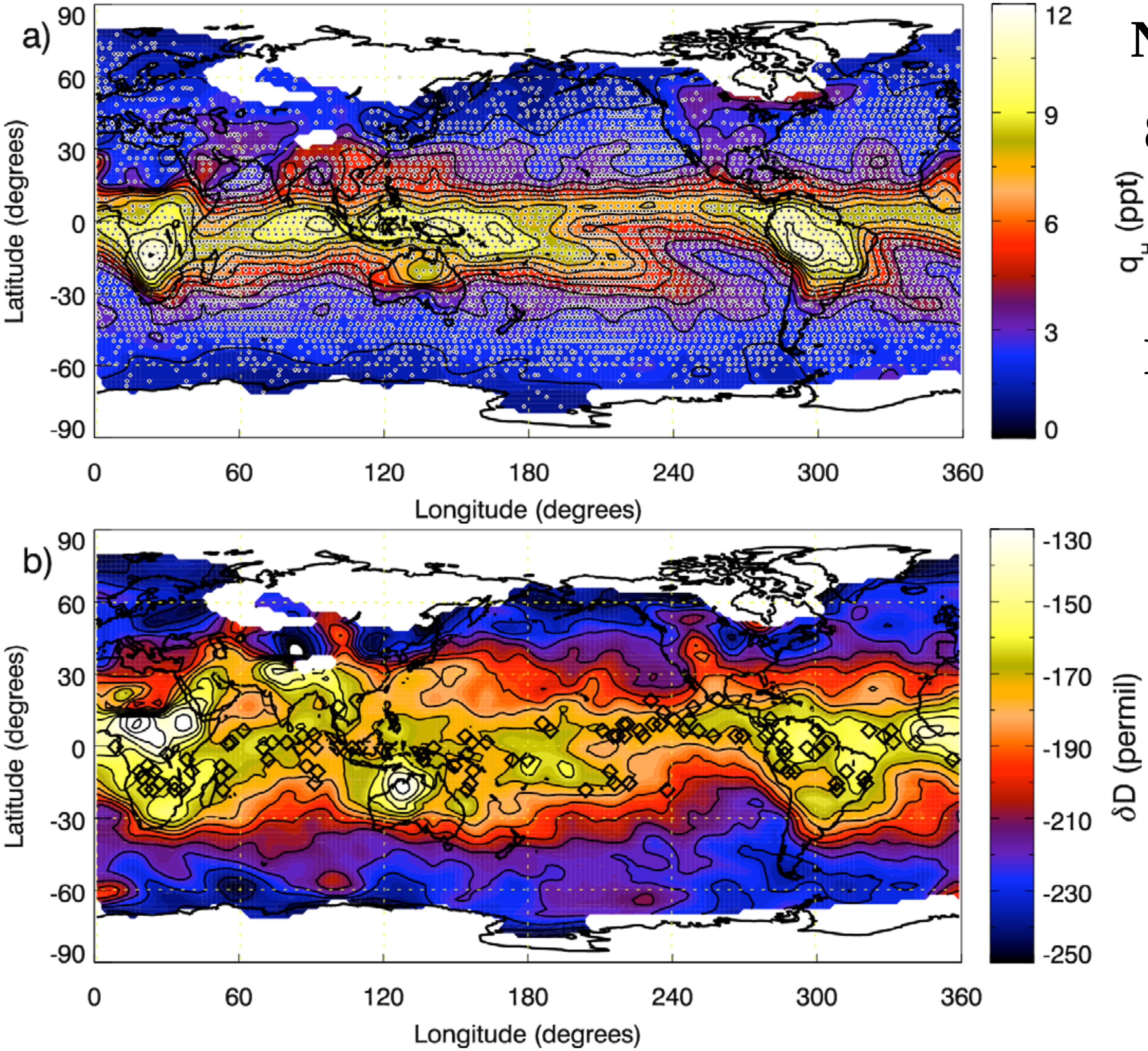
Evaporation

Returns to isotopic composition of the ocean source.

Conditions under which condensation occurs is different from the conditions when evaporation occurs, thus isotope state capture signal of flux

TES
Tropospheric Emission Spectrometer





November - March

850-550 hPa mean

H_2O (mmol/mol)

δHDO

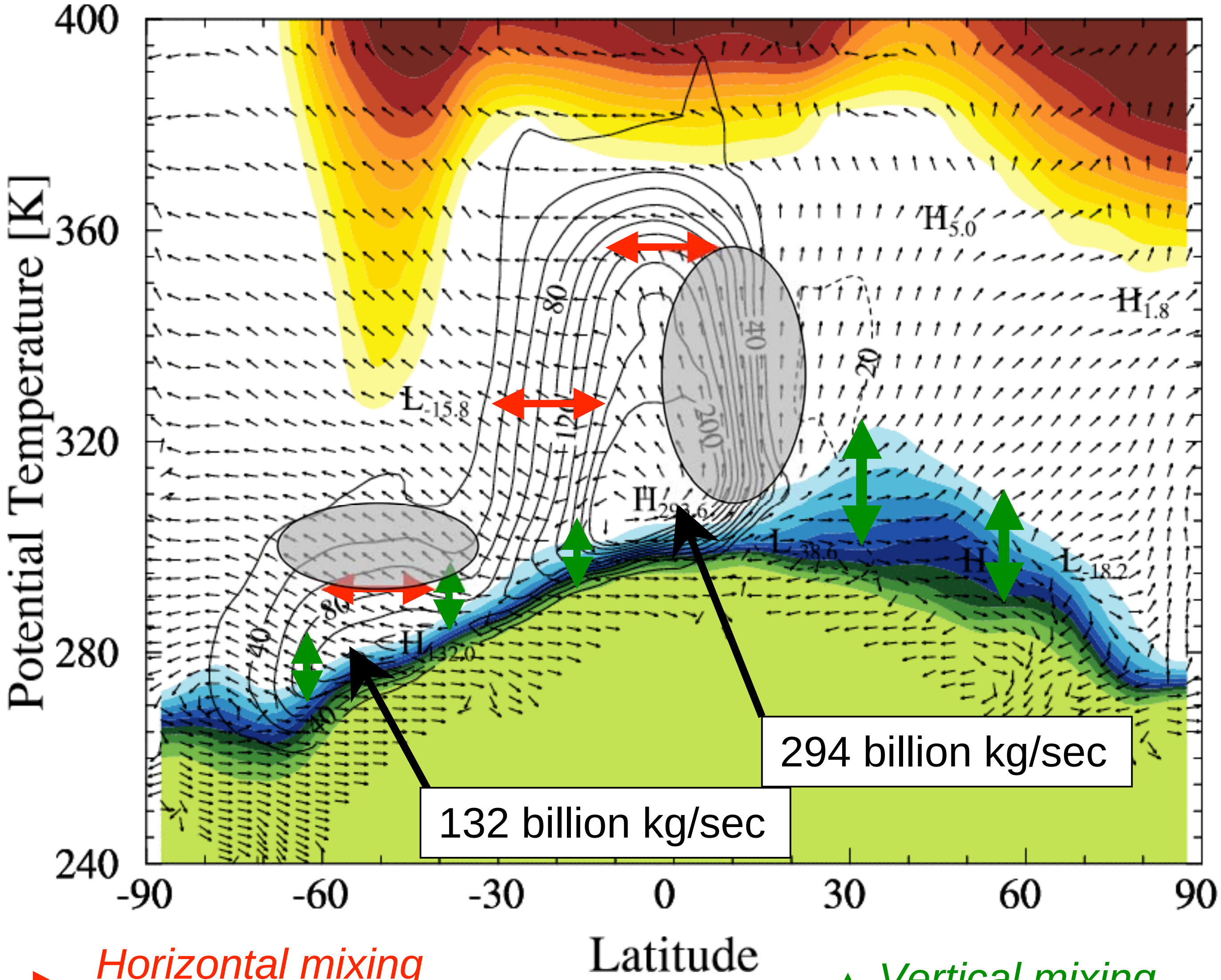
Gives sense of history.

“Aged” water at high latitudes

“New” water in tropics

Worden, Noone, Bowman et al. (2007)

(July)



Tropopause frequency

surface frequency

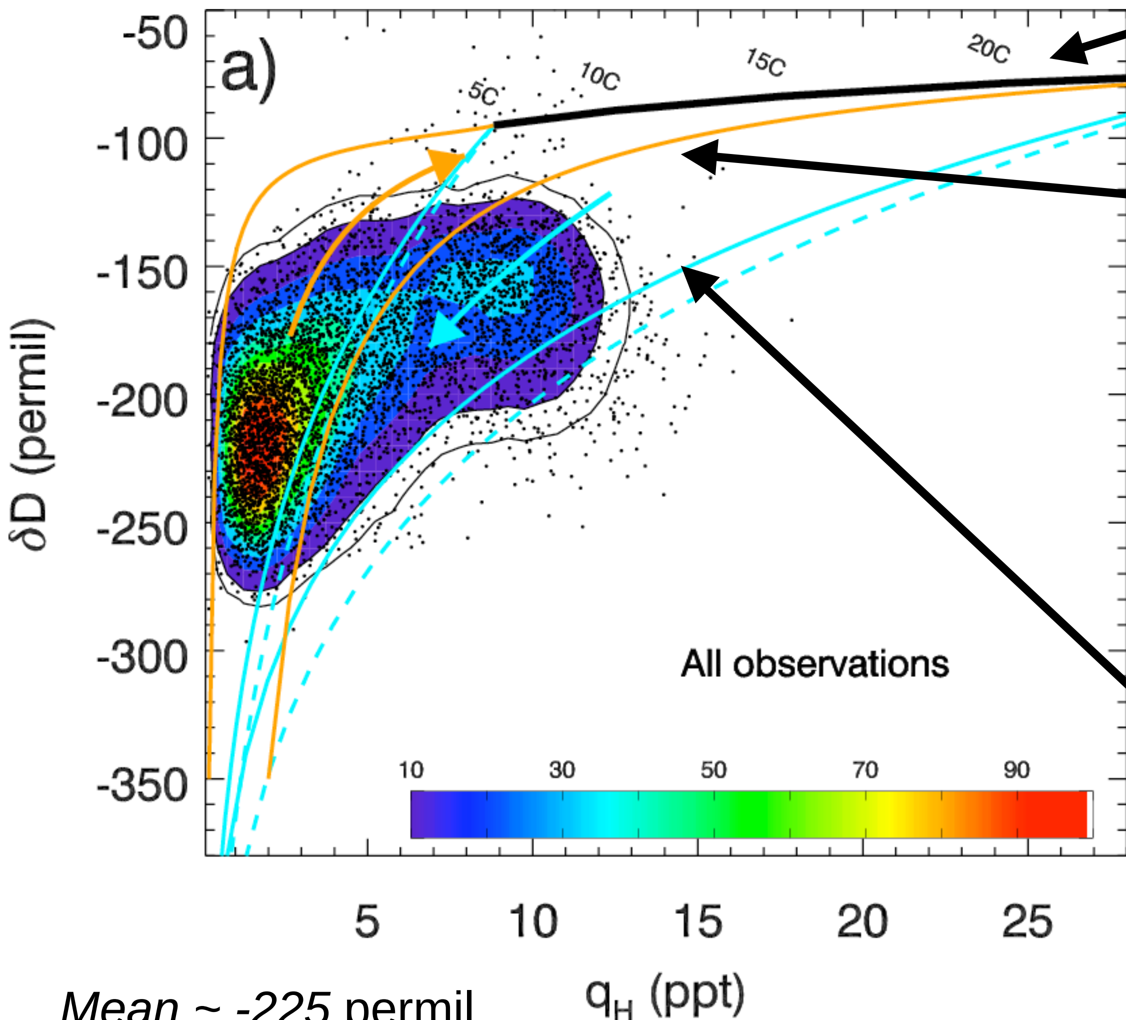
Horizontal mixing (synoptic eddies)

Vertical mixing (PBL turbulence)

MUGCM, R21L9, 5 years

Noone (submitted 2007)

The water *cycle*



Vapour in equilibrium with ocean water

Evaporation *("mixing")*

$$\frac{dq}{dt} = E = C(q_s - q)$$

$$\frac{dq_i}{dt} = E_i = C\eta(R_s q_s - Rq)$$

Rayleigh condensation

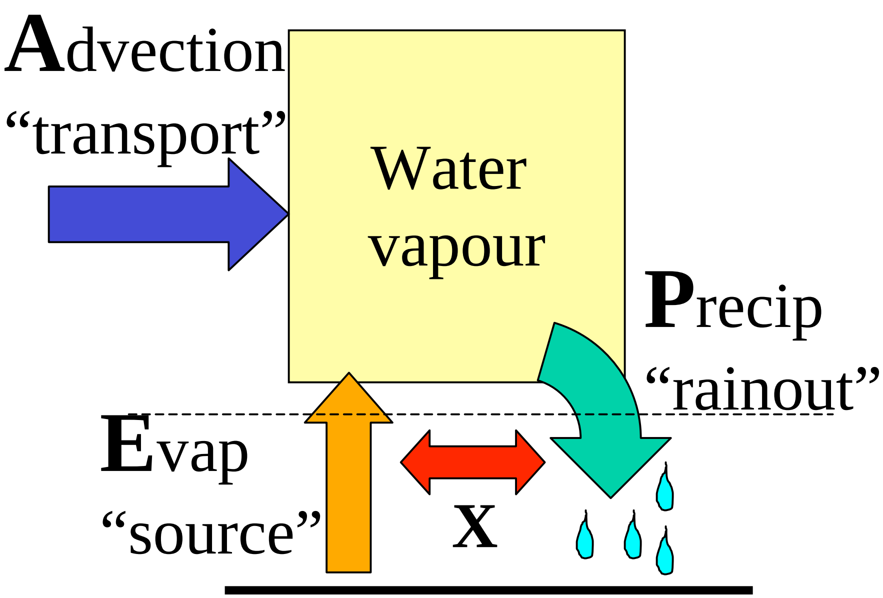
$$\frac{dq}{dt} = P$$

$$\frac{dq_i}{dt} = P_i = \alpha \frac{q_i}{q} P$$

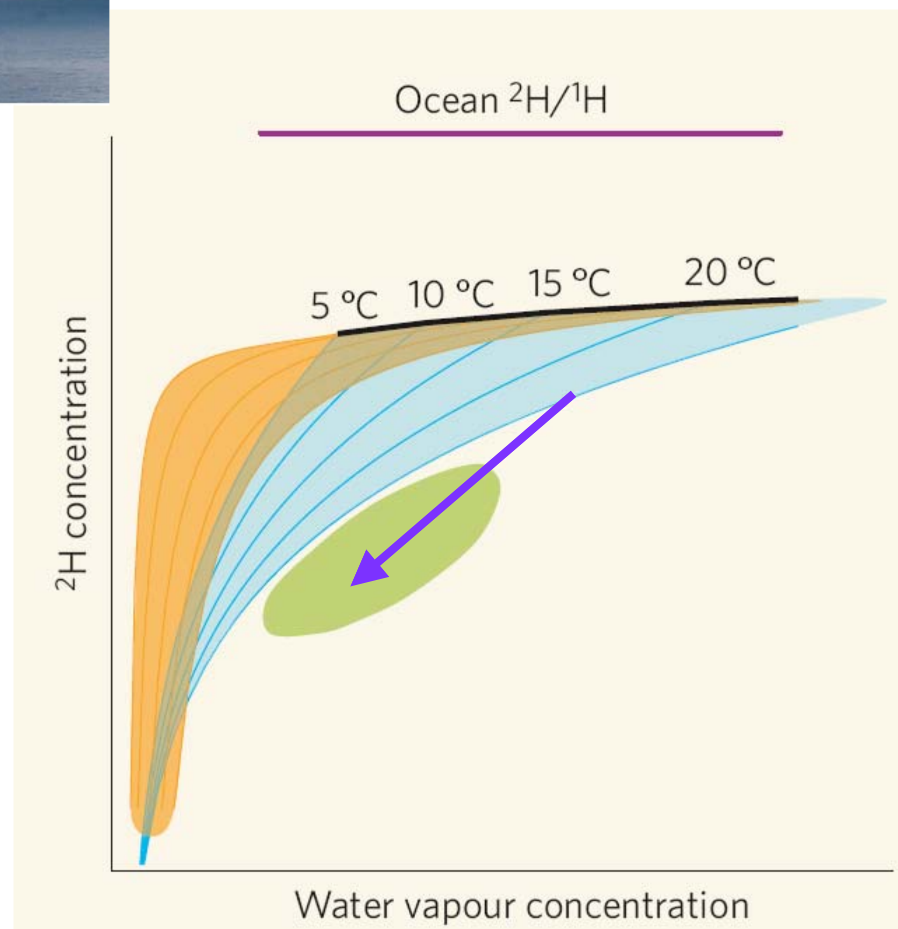
Mean ~ -225 permil

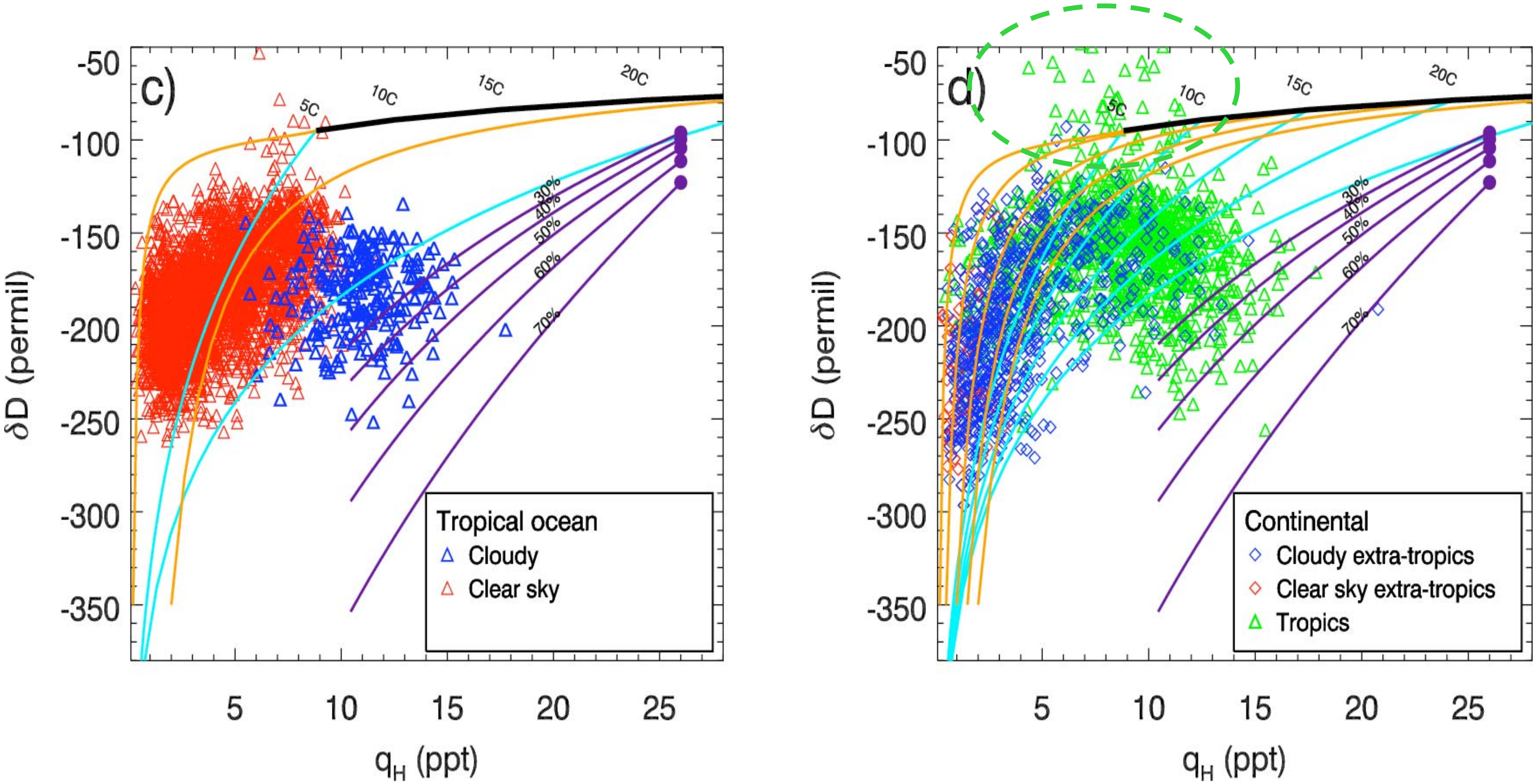
Controlled by balance of condensation and boundary layer supply of oceanic water

Fractionation efficiency $\alpha \sim 1.1$



Evaporation
of falling rain



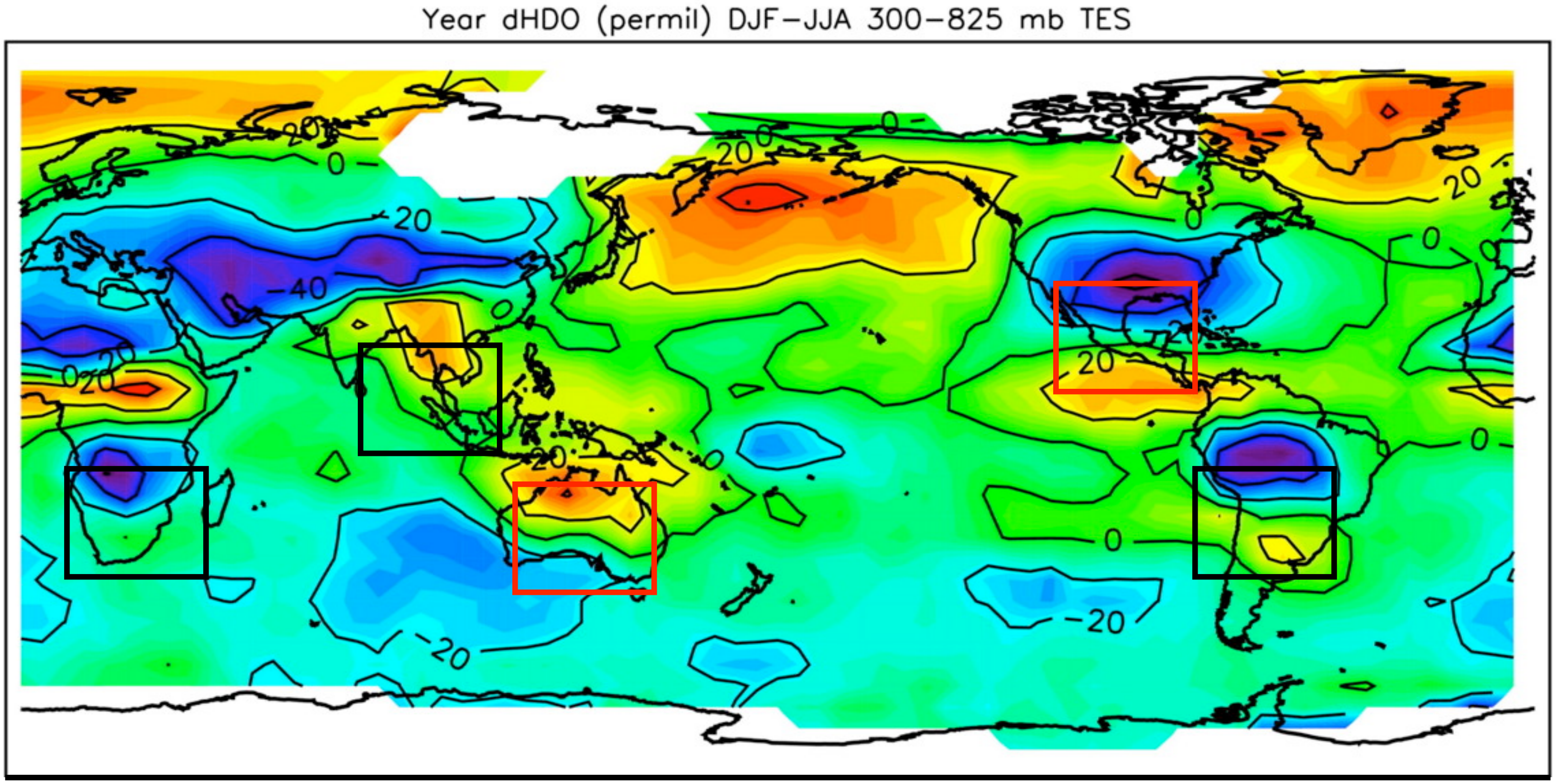


Requires rain to be evaporated to explain distribution of cloudy points, since this gives and “extra” fractionation

Mass balance shows 20-50 % of rain evaporation needed

Enriched values can not be from ocean – signal of transpiration

Seasonal difference



Wet season depletion - “amount effect”, evaporation of falling rain (conditions dominated by condensation processes)

Wet season enrichment? Different balance of fluxes.

Hypothesis: Lofting of vapor and detrainment (i.e., identification of local versus long-ranged transport)

Atmospheric isotope balance

H_2O: $$\boxed{\frac{dq}{dt} = E - P + A}$$

HDO: $$\frac{dq_i}{dt} = E_i - P_i + A_i$$

$$\boxed{\frac{\partial\delta}{\partial t} = \frac{E}{q}\left(\delta_s - \delta - \varepsilon_s\right) - \frac{P}{q}\left(\delta_p - \delta + \varepsilon_c\right) + \frac{A}{q}\left(\overline{\delta} - \delta\right)}$$

Isotope rules

$A_i = \overline{R}A$ Upstream known

$\frac{P_i}{P} = \alpha\frac{q_i}{q}$ Rayleigh

$E = C(q_s - q)$ Mixing to

$E_i = C\eta(R_s q_s - Rq)$ infinite source

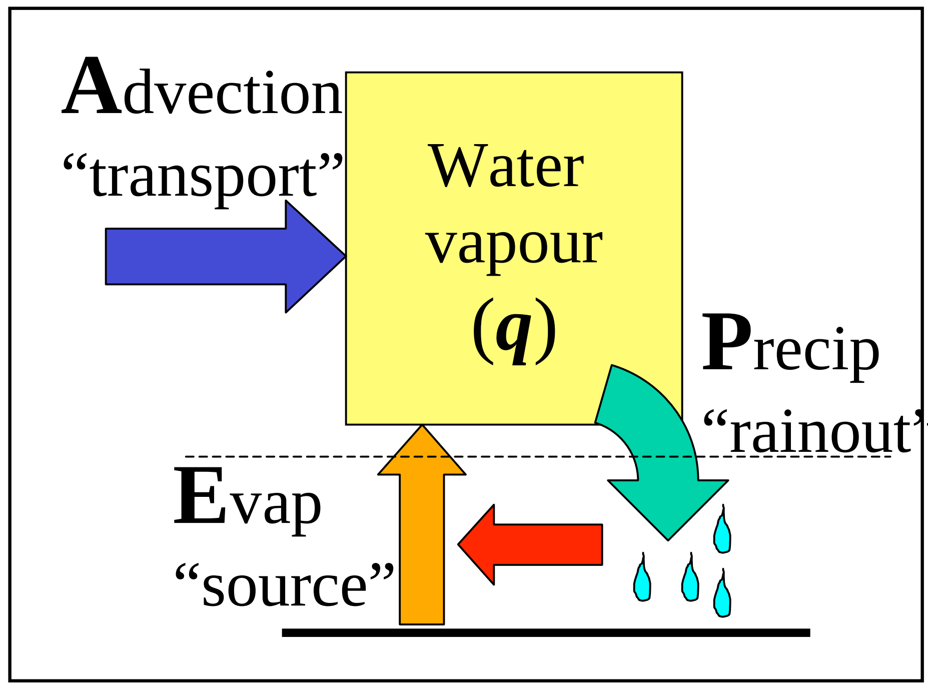
At steady state, have the balance

$$\boxed{\hat{\delta} = \frac{r_S\left(\delta_s - \varepsilon_s\right) - r_P\left(\delta_p + \varepsilon_c\right) + r_A\overline{\delta}}{r_S + r_P + r_A}}$$

Rate constants:

$r_S = E/q$, $r_P = P/q$ and $r_A = A/q$.

These characterize the hydrology.



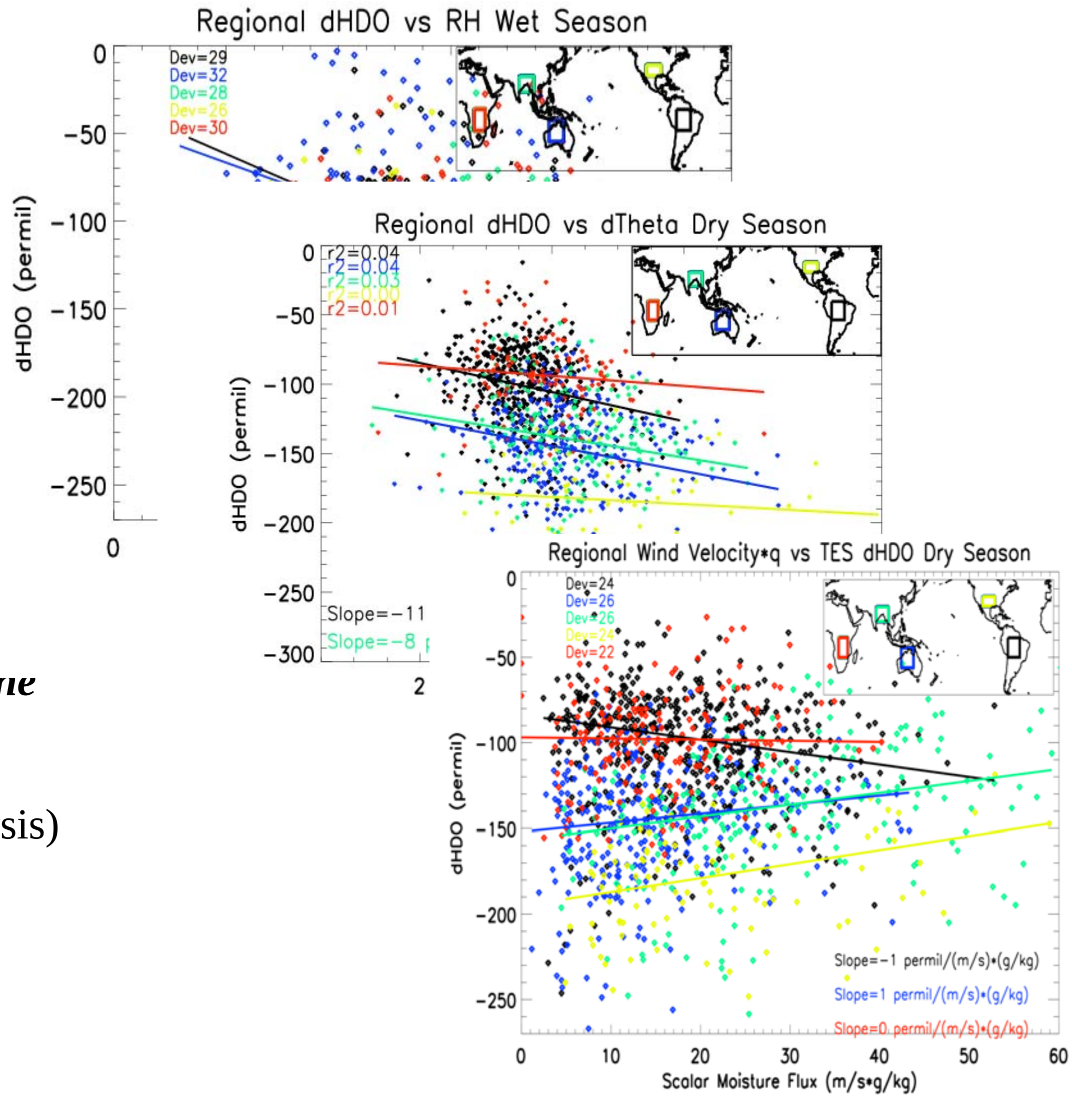
Estimate of hydrologic rate constants

- Condensation (P):
  (precip amount, RH)
- Evap/source (E):
  (turbulence, lapse rate)
- Advective source (A)
  (scale moisture flux *qv*)

Three sets of processes constrain the three rates, and can be estimated

This can be used to ensure integrated sensor data is merged in a way that the balance of processes is well resluved

(A task well suited to assimilation/reanalysis)



Brown, Worden and Noone (2006), Brown and Noone (in prep)

Conclusions

Water isotopes necessarily integrative
(e.g., link atmosphere to soil water as transpiration/evaporation, deposition processes over ice sheets)

Ensure the budgets are met for the right reason.
(i.e., need correct combination of multiple processes)

1. Budget calculations of HDO and H_2O can give P ***and*** E (rather than P-E)
2. Hydrologic budgets as balance of ***fluxes*** directly from observations of isotope ***state***.
3. Isotope balance capture strength of overturning water circulation and tropical cycling
4. Transpiration from land surfaces is an important source of water for the tropical troposphere
5. Evaporation of falling rain important in the tropics (20-50%),

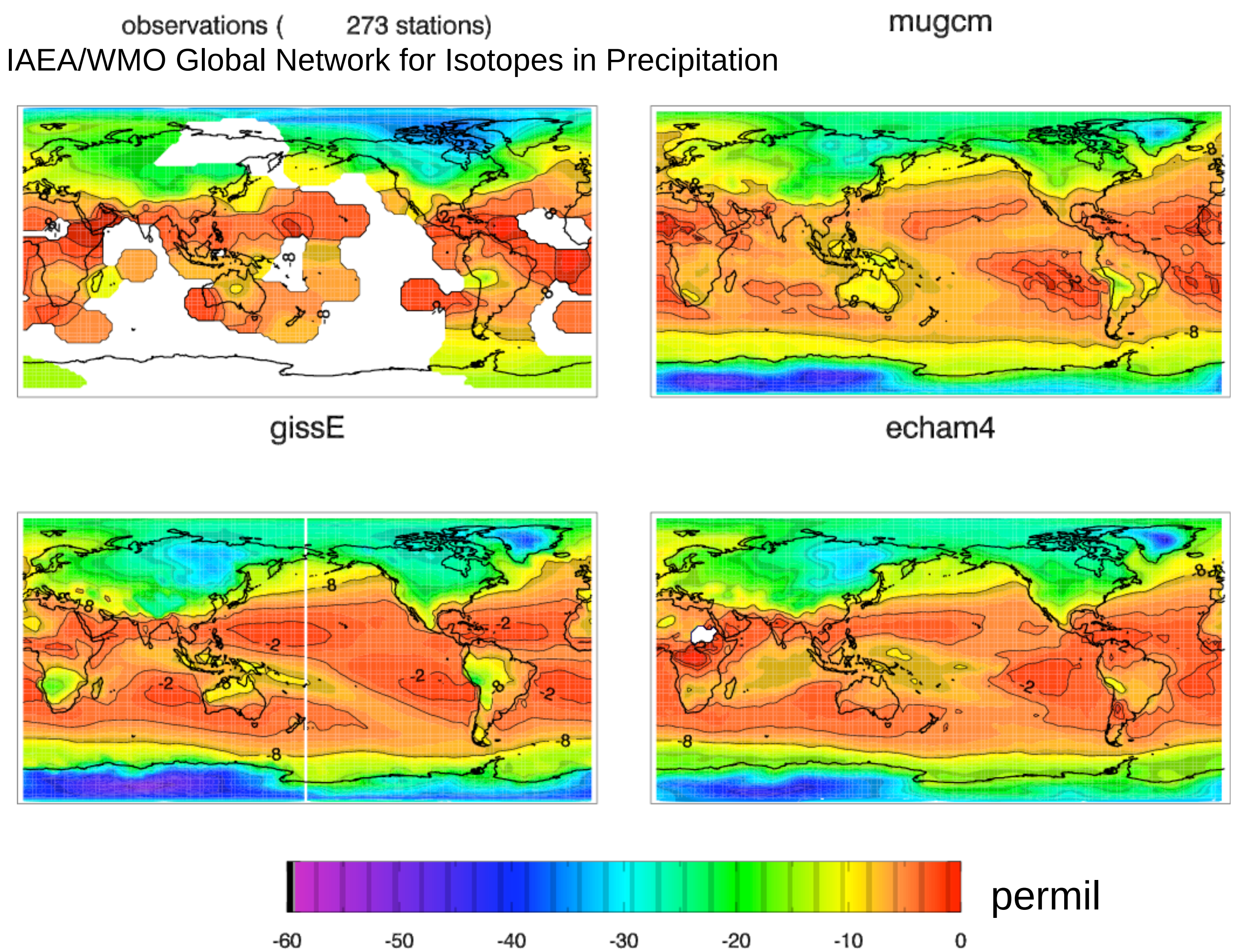
6. While climate models get hydrology OK, isotopes show this is for the wrong reason (P, E, A)
(results from GEWEX SWING isotope intercomparison, guidance for model development)

TES has limitations

- Would like ***boundary layer observations*** (lower than 800hPa)
- Better ***temporal sampling*** will greatly assist assimilation
- Better ***spatial sampling*** will help understand clouds (updraft/detrainment)
- Better spectral observations will allow multiple isotopologues (HDO, $H_2{}^{18}O$, maybe $H_2{}^{17}O$)
(one can imagine an instrument system that combines UR, UV and microwave)
- Need long (multi-year) dataset to interpret climate state

- No follow-on mission planned for US or other. TES life to 2010 (?)

$\delta^{18}O$ in precipitation (January)

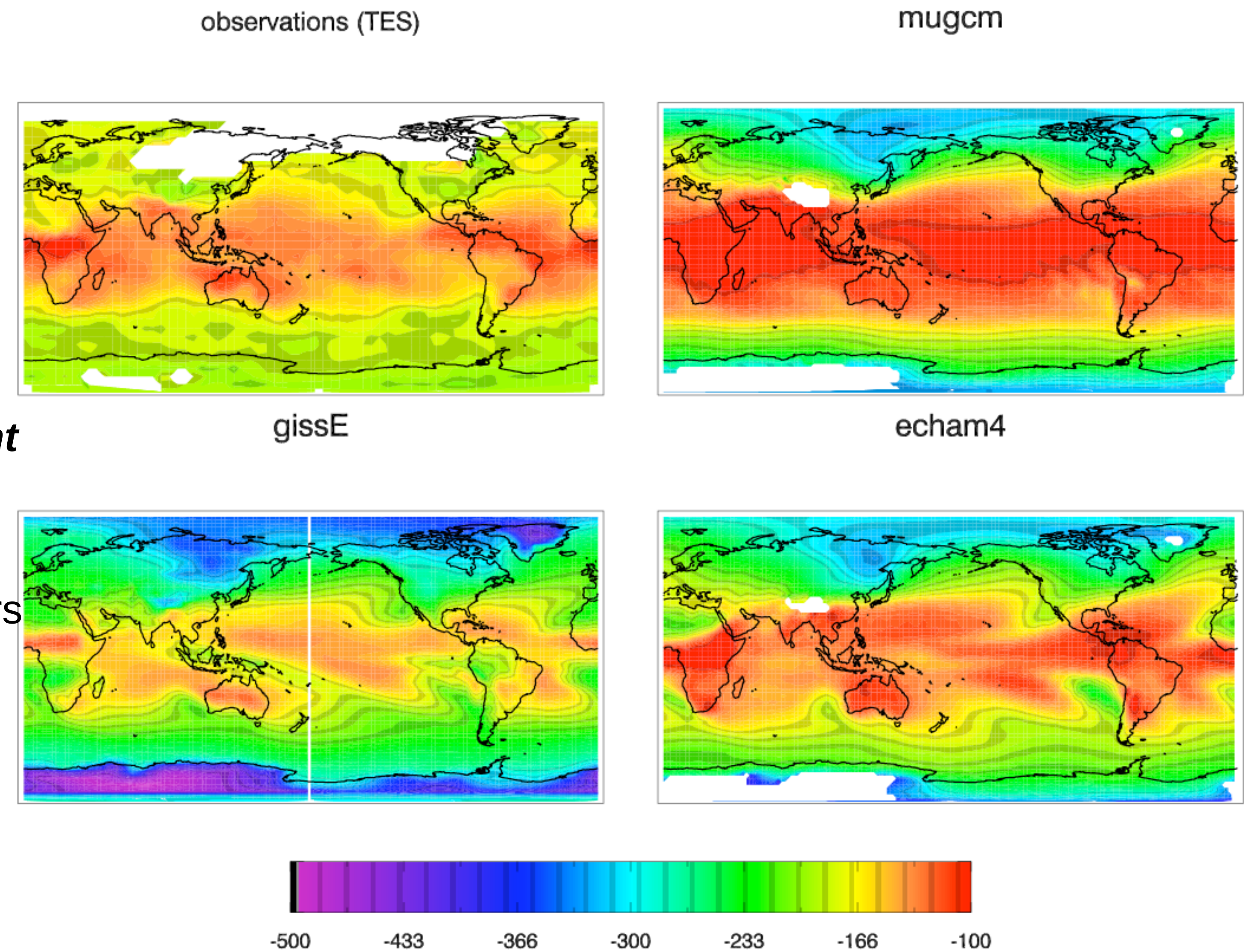


Water vapour HDO ~700 hPa (January)

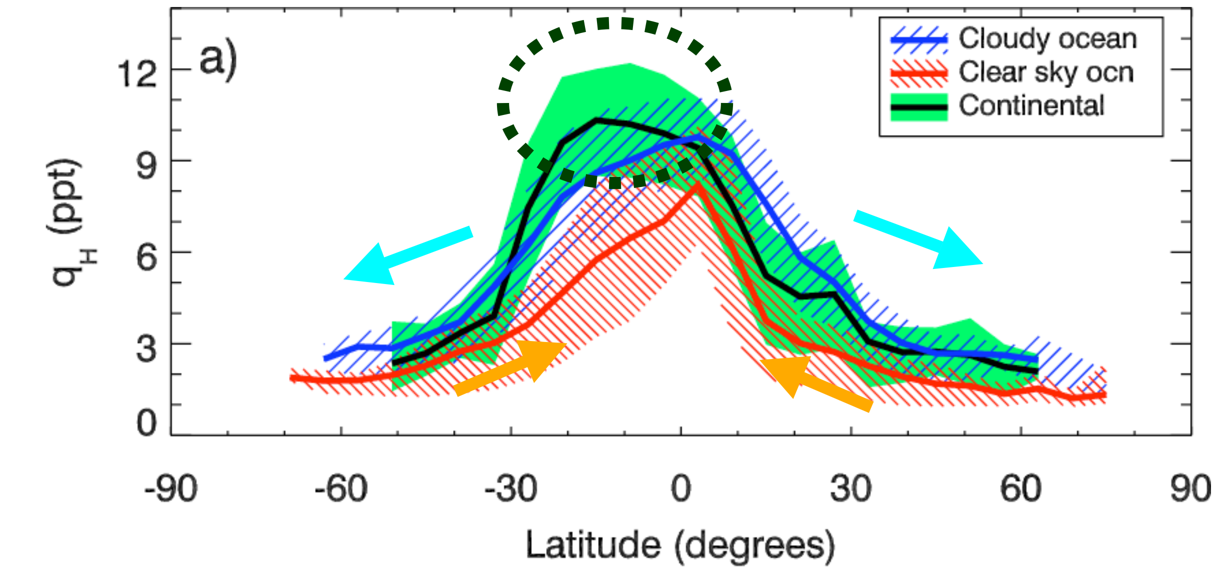
NASA Tropospheric Emission Spectrometer (on Aura)

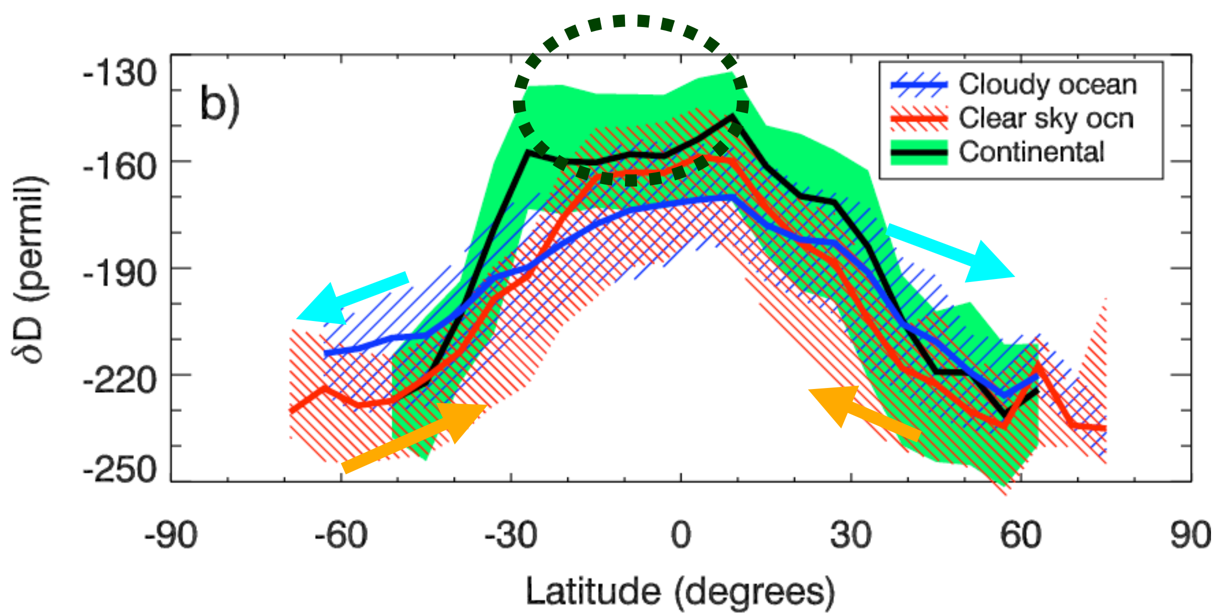
New independent test!

First validation of models in 30 years of isotope modeling!



A few extras





TES Observations

Moist ocean

RH > 50%, OD > 0.7
(poleward branch)

Dry ocean

RH < 30%, OD > 0.1
(equatorward return flow)

All land

Notice land is quite exceptional.

More water,
more depleted

(i.e., a missing flux)

•Fourier transform spectrometer

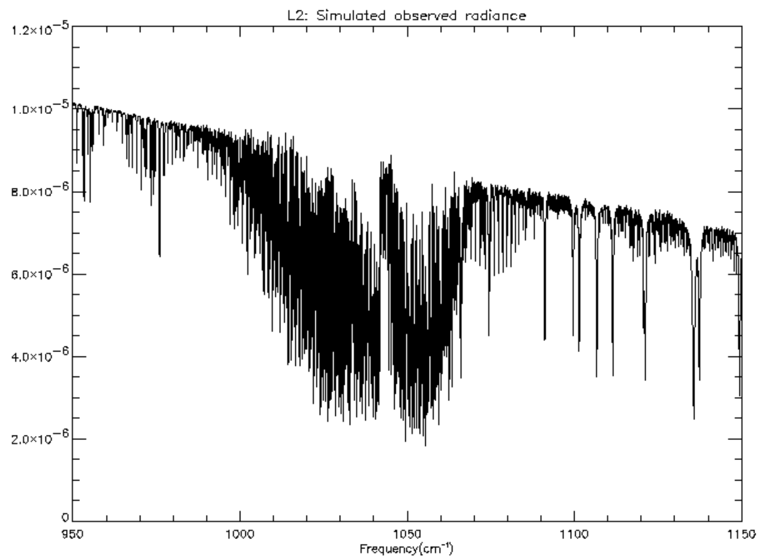
•Thermal infra-red (650 – 3050 cm^{-1})

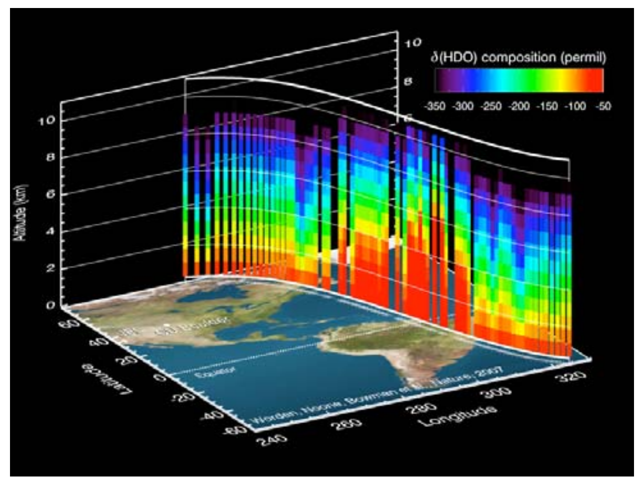
•Individual lines resolved (0.06 cm^{-1})

•Primary mission O_3, CO, CH_4

•Micro-window contains H_2O, CO_2, HDO and $H_2{}^{18}O$ lines.

•Bayesian non-linear retrieval minimizes error in covariance HDO/H_2O to precise isotope *ratio*



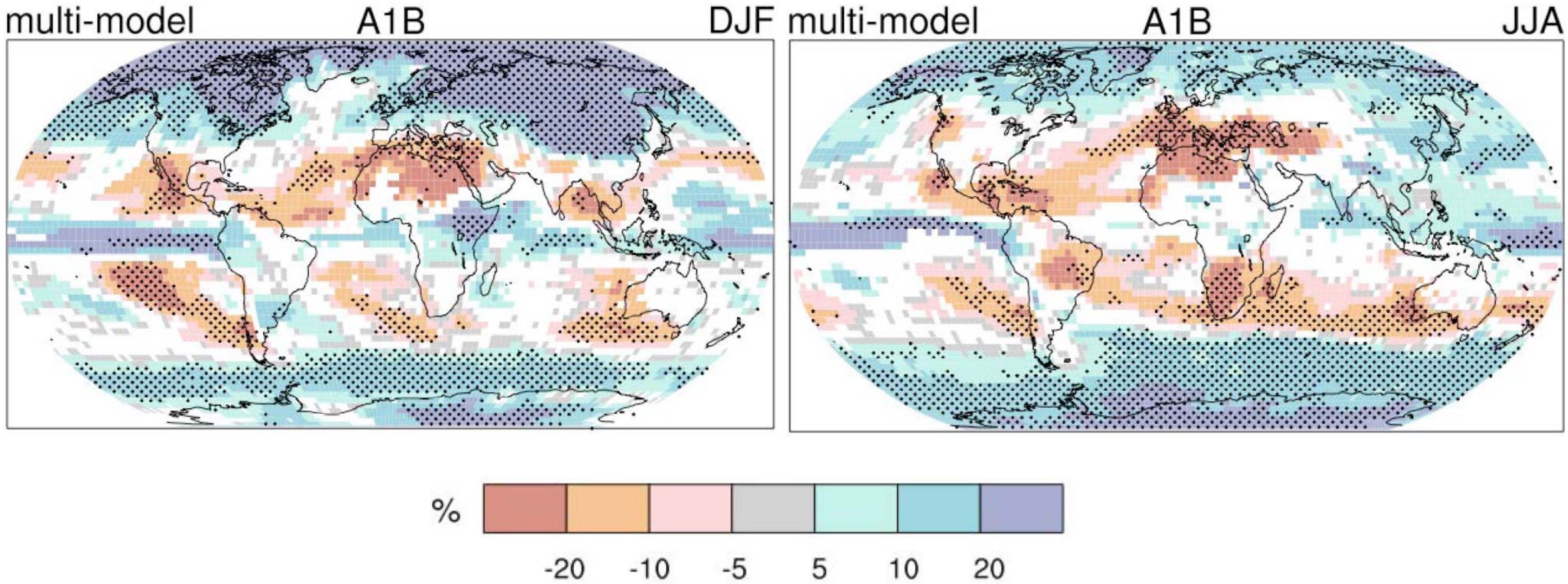


~10 km hoz. resolution,
~200 km sampling,
~ 1 d.o.f. in vertical

Worden, Bowman, Noone, et al. (2006)

IPCC projected precipitation

Percentage change 2080-2090 relative to 1980-1999.



Patterns of changes linked to overturning circulation.

But which set of hydrologic processes have changed?

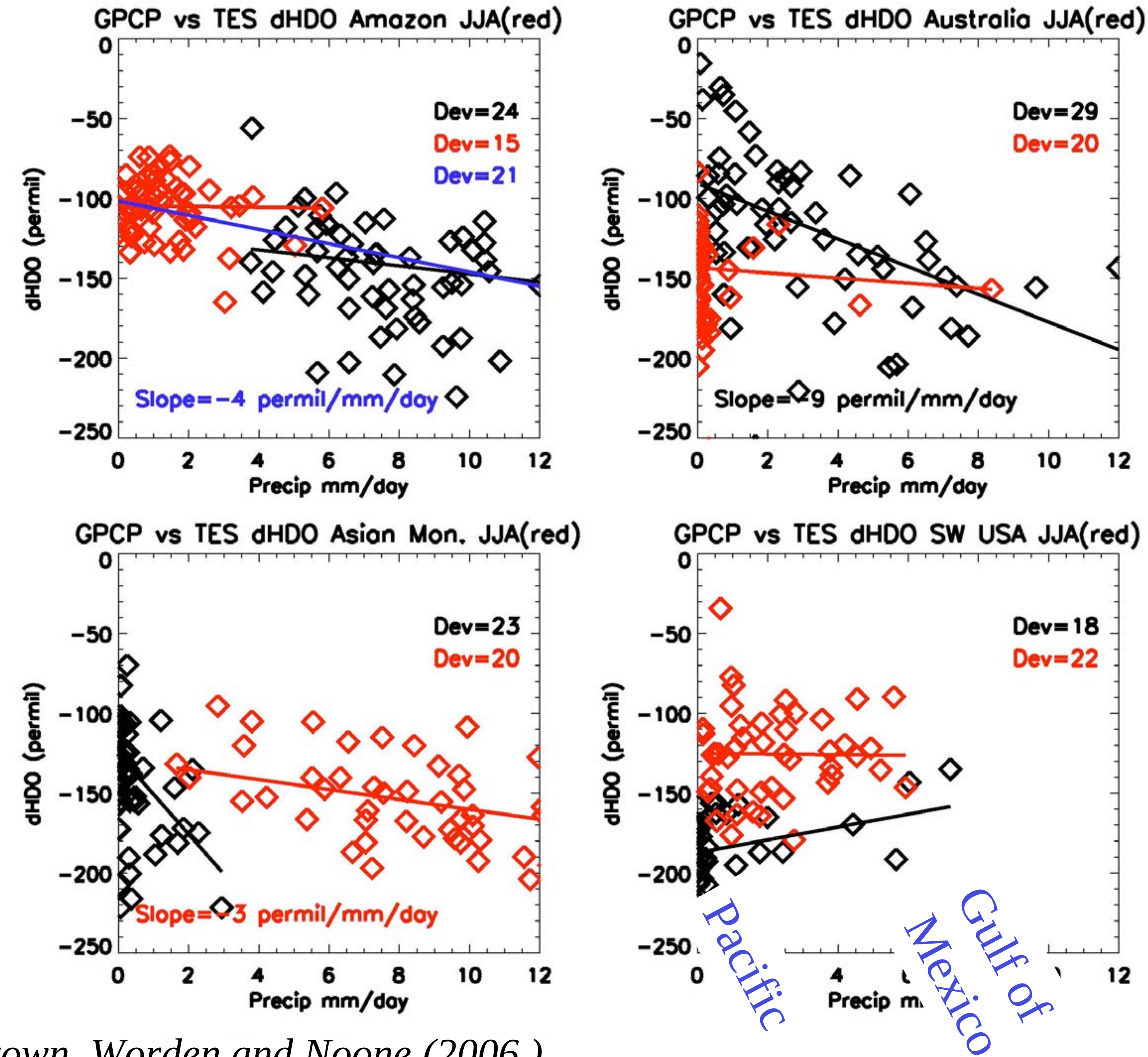
IPCC, Fourth Assessment, Summary for Policy Makers, Feb 2007.

A question of estimation

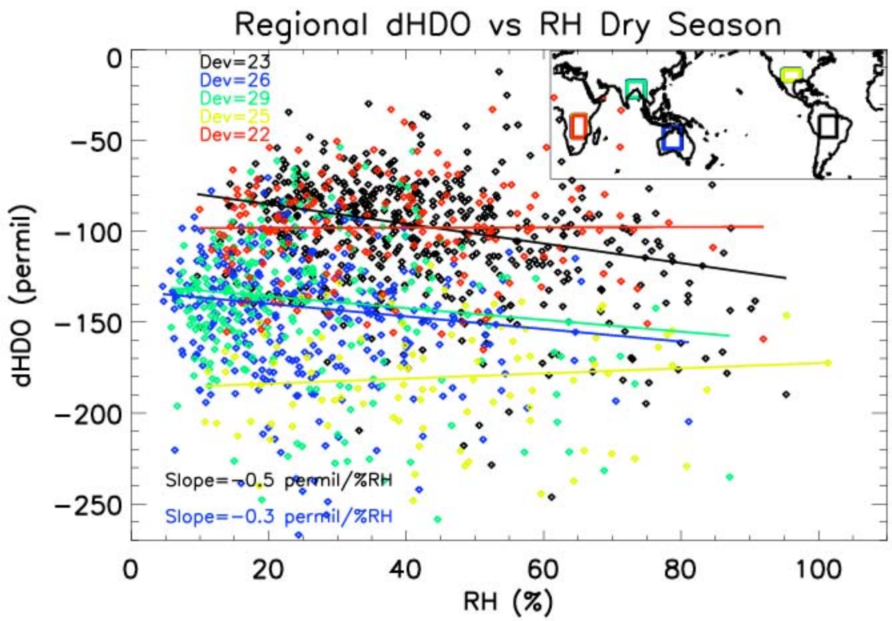
- Obtain some estimate the magnitude of the source/sink terms given a known distribution of observations.
  (advective rate, recycling rate, also transpiration fraction)

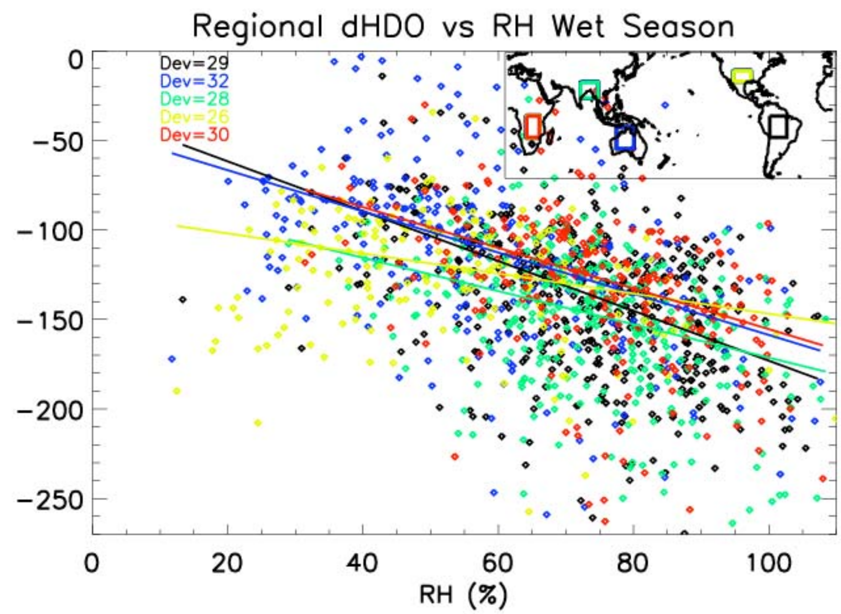
- Data assimilation is a viable option
- Simple regression models are more direct
- Correlations are not large
- Scatter is real variability (not noise)
- Large number of observations needed to compute climatological values of local hydrologic rates

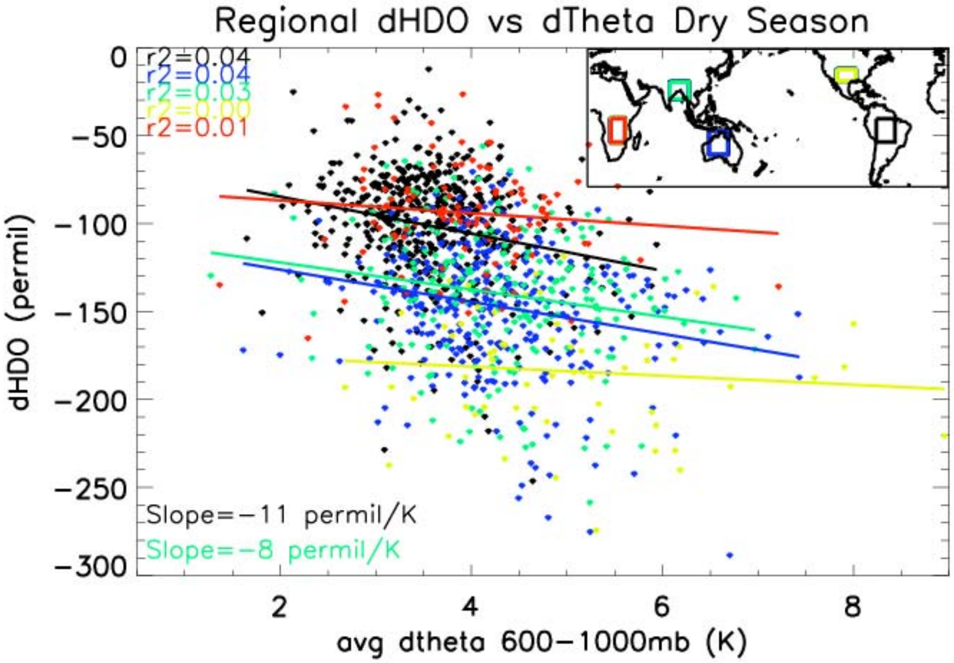
- *Here this was presented by induction,*
  and demonstrates this is within reach

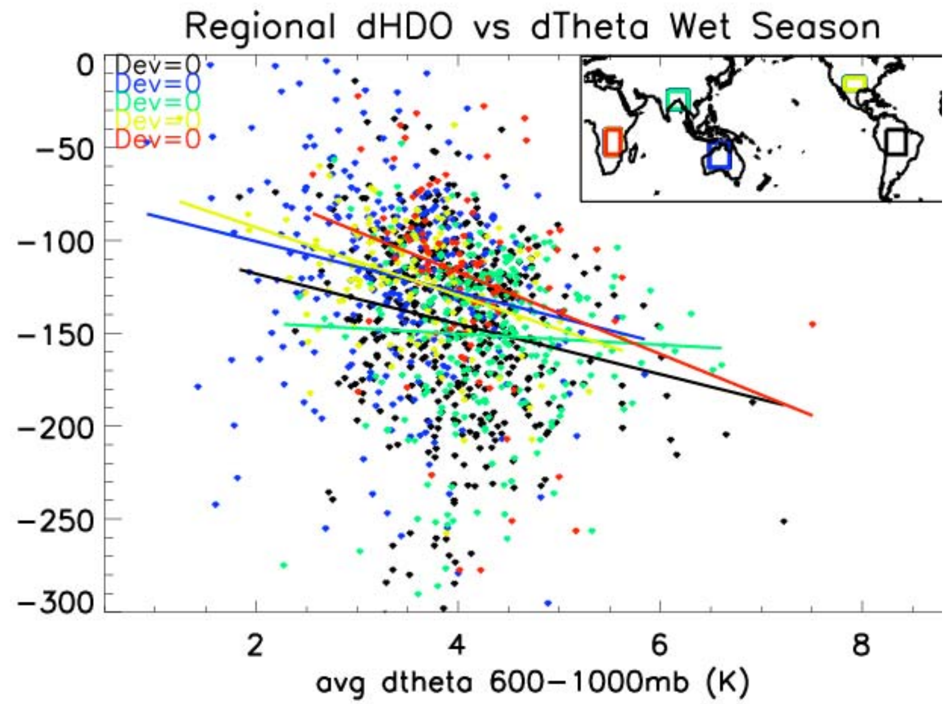


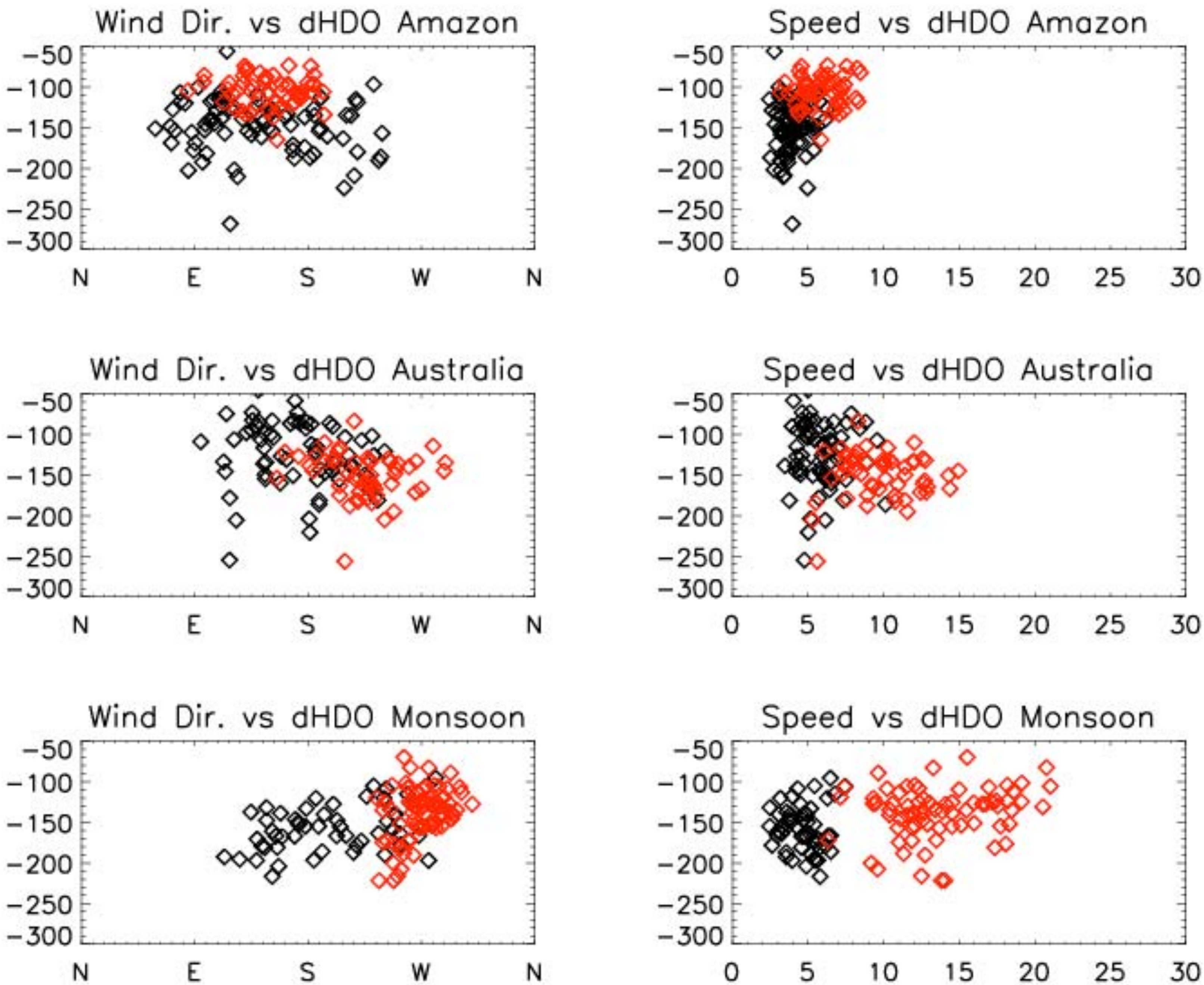
Brown, Worden and Noone (2006),


Regional dHDO vs RH Dry Season
Dev=23
Dev=26
Dev=29
Dev=25
Dev=22
Slope=−0.5 permil/%RH
Slope=−0.3 permil/%RH
dHDO (permil)
RH (%)
0
−50
−100
−150
−200
−250
0
20
40
60
80
100

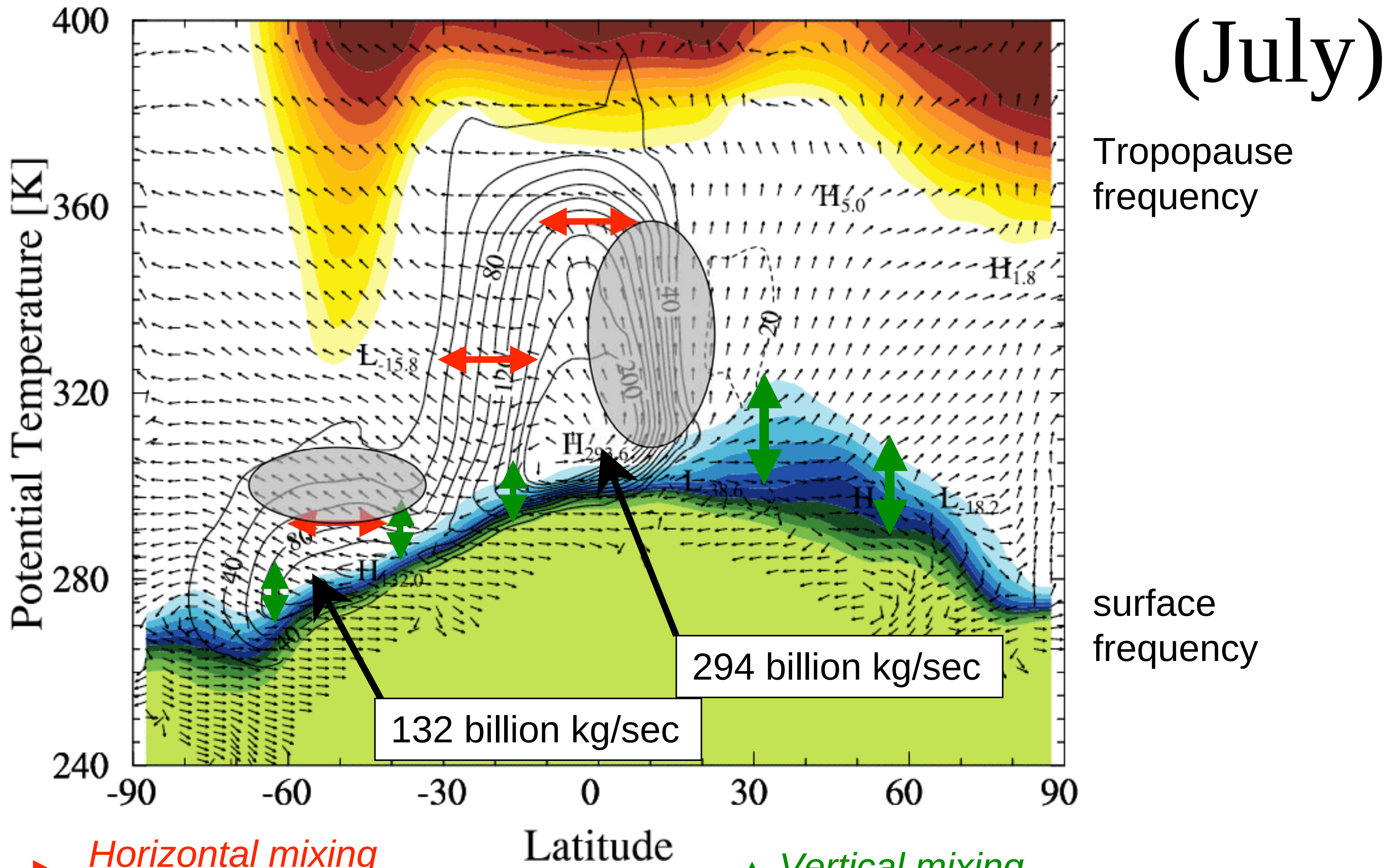

Regional dHDO vs RH Wet Season
Dev=29
Dev=32
Dev=28
Dev=26
Dev=30
RH (%)
0
−50
−100
−150
−200
−250
0
20
40
60
80
100


Regional dHDO vs dTheta Dry Season
r2=0.04
r2=0.04
r2=0.03
r2=0.00
r2=0.01
Slope=−11 permil/K
Slope=−8 permil/K
dHDO (permil)
avg dtheta 600−1000mb (K)


Regional dHDO vs dTheta Wet Season
Dev=0
Dev=0
Dev=0
Dev=0
Dev=0
avg dtheta 600−1000mb (K)



Wind Dir. vs dHDO Amazon
Speed vs dHDO Amazon
Wind Dir. vs dHDO Australia
Speed vs dHDO Australia
Wind Dir. vs dHDO Monsoon
Speed vs dHDO Monsoon
−50
−100
−150
−200
−250
−300
N
E
S
W
N
0
5
10
15
20
25
30



Horizontal mixing (synoptic eddies)

Vertical mixing (PBL turbulence)

MUGCM, R21L9, 5 years

Noone (submitted 2007)